



Electrical Materials Research for NASAs Hybrid Electric Commercial Aircraft Program

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Who is Funding Electrical Materials Work at NASA?



Strategic Thrusts Guide NASA Investment Decisions



6 Strategic Thrusts



Safe, Efficient Growth in Global Operations

Enable full NextGen and develop technologies to substantially reduce aircraft safety risks



Innovation in Commercial Supersonic Aircraft

Achieve a low-boom standard



Ultra-Efficient Commercial Vehicles

Pioneer technologies for leaps in efficiency and environmental performance, i.e. blended wings, small-core turbine engines



Transition to Low-Carbon Propulsion

Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology



Real-Time System-Wide Safety Assurance

Develop an integrated prototype of a real-time safety monitoring and assurance system



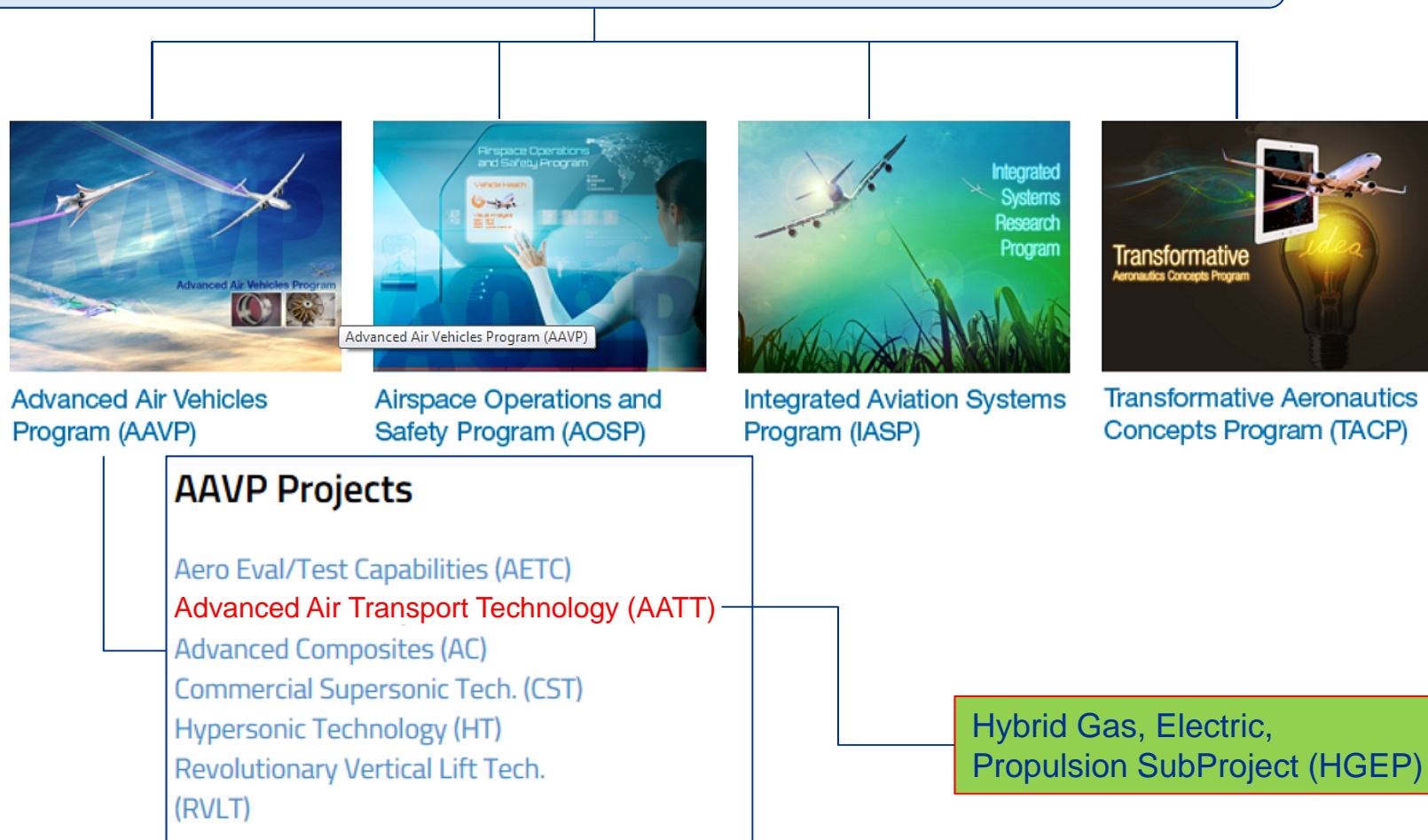
Assured Autonomy for Aviation Transformation

Develop high impact aviation autonomy applications

Program Hierarchy



Aeronautics Research Mission Directorate (ARMD)



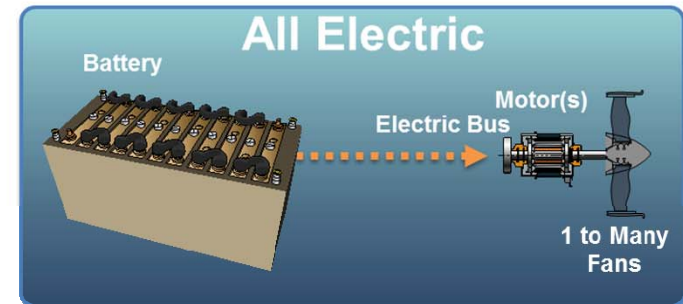
Electrified Aircraft Propulsion Terminology



Electrified Propulsion:

Refers to the use of electric power for aircraft propulsion

- Could be all or partially electric propulsion



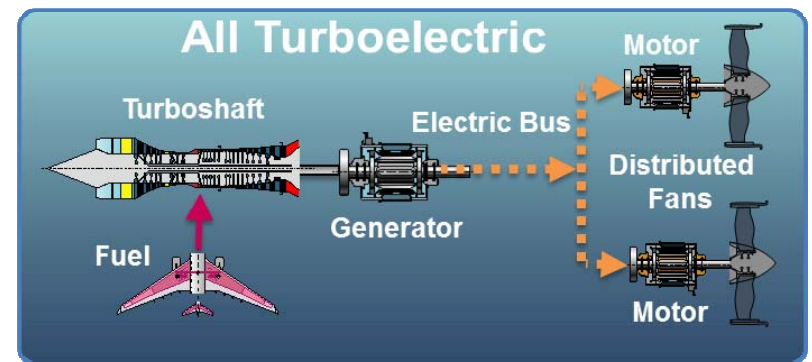
- Hybrid Electric has two meanings in aircraft context

- One meaning is the use of **two power sources**, such as turbine engine and electric energy storage, to drive the same fan or propeller shaft—hybrid electric powertrain
- Another meaning is the **combination of more than one propulsive sources** such as traditional turbofan engines augmented with electric drive enabled propulsion—hybrid electric propulsion

- Turboelectric Propulsion:

Use onboard generation as power source to drive fans or propellers

- Turboelectric generation already provides electric power for secondary systems on aircraft

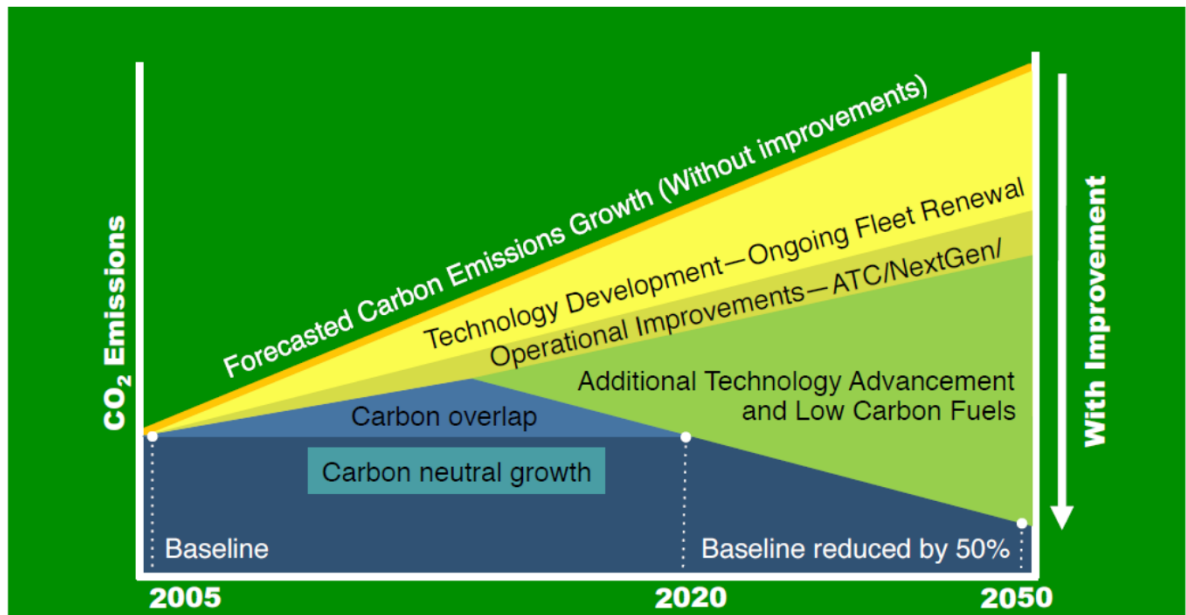


Strategic Thrust 4 Low Carbon Propulsion



Reduce fossil fuel usage and carbon emission while allowing aviation growth

- The Low Carbon Propulsion challenge is to enable carbon-neutral growth in aircraft operations.
- The proposed answer is a combination of alternative fuels and alternative propulsion



2015

2025

2035

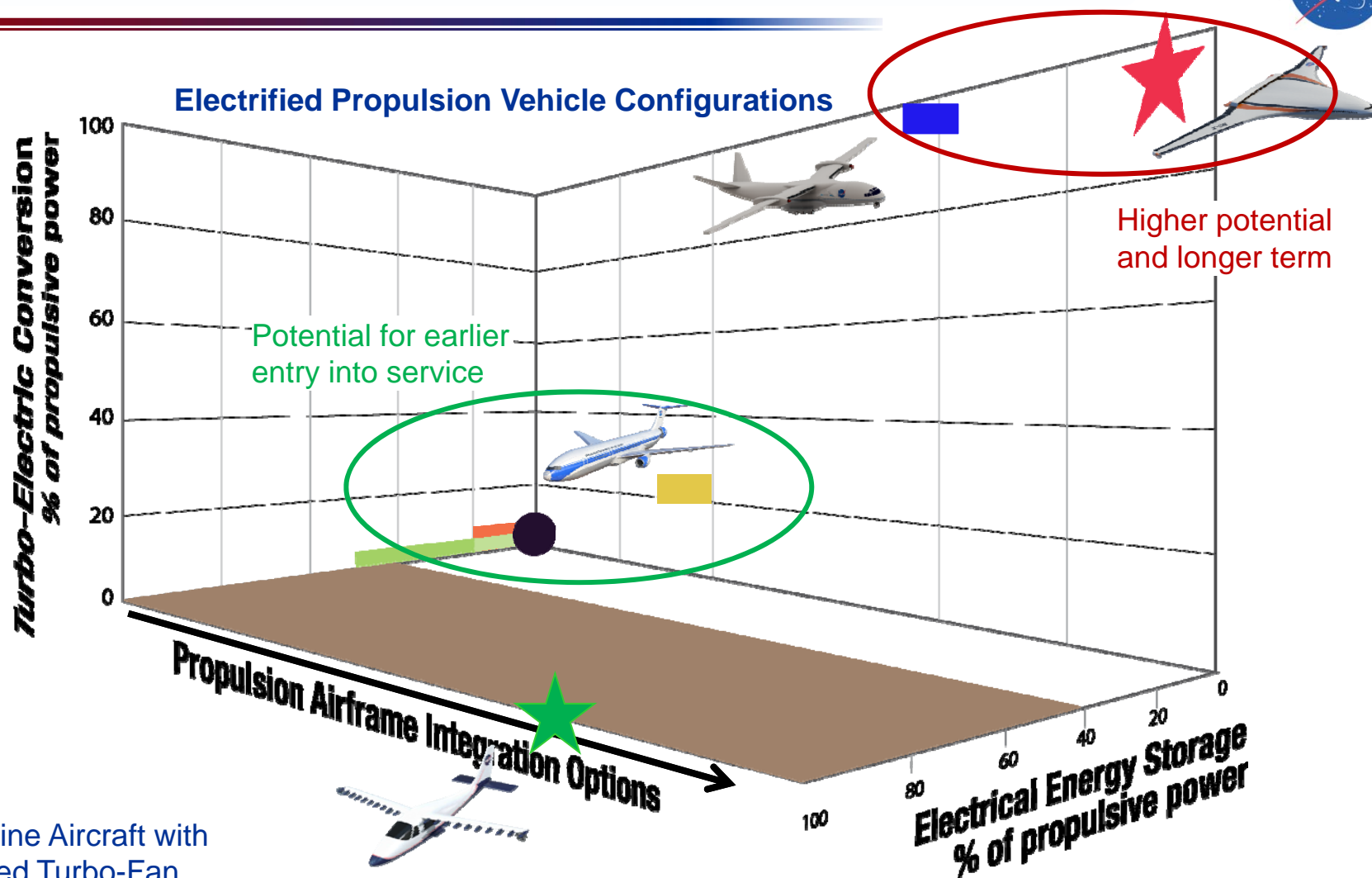


Introduction of Low-Carbon Fuels for Conventional Engines and Exploration of Alternative Propulsion Systems

Introduction of Alternative Propulsion Systems at a Small Scale

Introduction of Alternative Propulsion Systems to Aircraft of All Sizes

Electric options open the airplane design space



● Baseline Aircraft with Podded Turbo-Fan

★ X-57 Maxwell 4 PAX Plane

■ AATT 50 PAX Studies

■ SUGAR VOLT 150 PAX Study

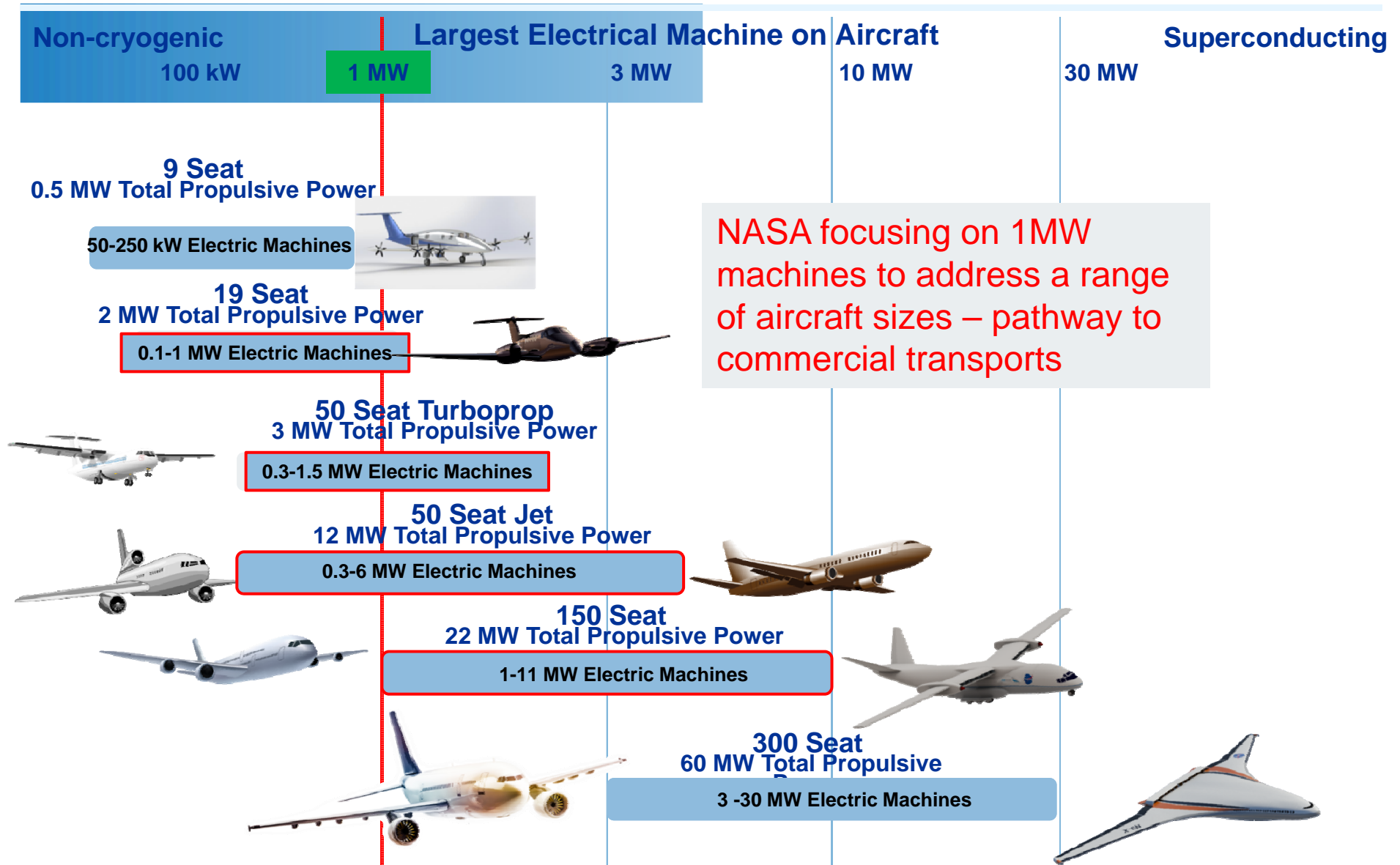
■ Current NRA 150 PAX Studies

■ STARC-ABL 150 PAX Study

■ ECO-150 150 PAX Studies

★ N3-X 300 PAX Turbo-Electric

Machine Power Relevant to Aircraft Class



Configurations Drive the Technology Investment



The technology development needs determined from configuration studies

- When selecting technology development investments, start with the technologies common to both.

Energy Storage	Electrical Dist.	Turbine Integration	Aircraft Integration
Battery Energy Density	High Voltage Distribution	Fan Operability with different shaft control	Stowing fuel & batteries; swapping batteries
Battery System Cooling	Thermal Mang't of low quality heat	Small Core dev't and control	Aft propulsor design & integration
	Power/Fault Mang't	Mech. Integration	Integrated Controls
	Machine Efficiency & Power	Hi Power Extraction	
	Robust Power Elec.		
Parallel Hybrid Specific	Common to both	Turboelectric Specific	

Rationale for Material Investment

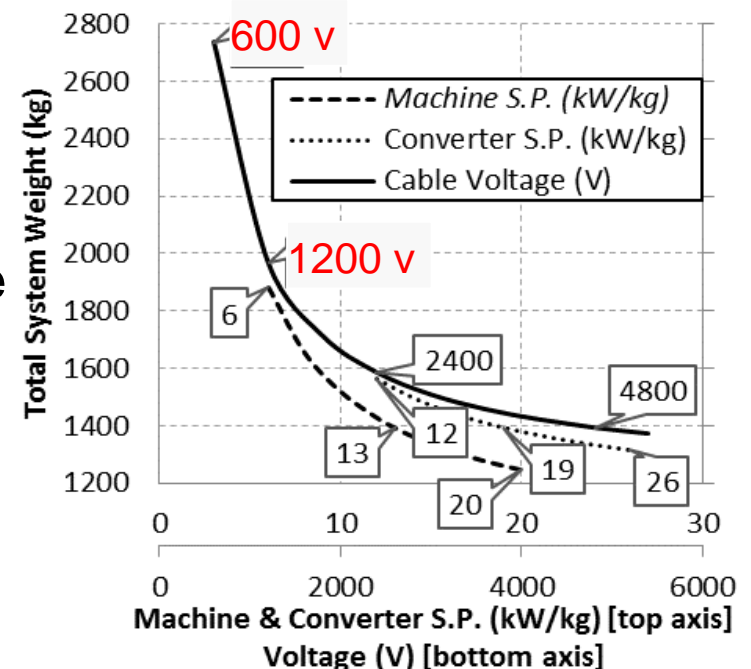
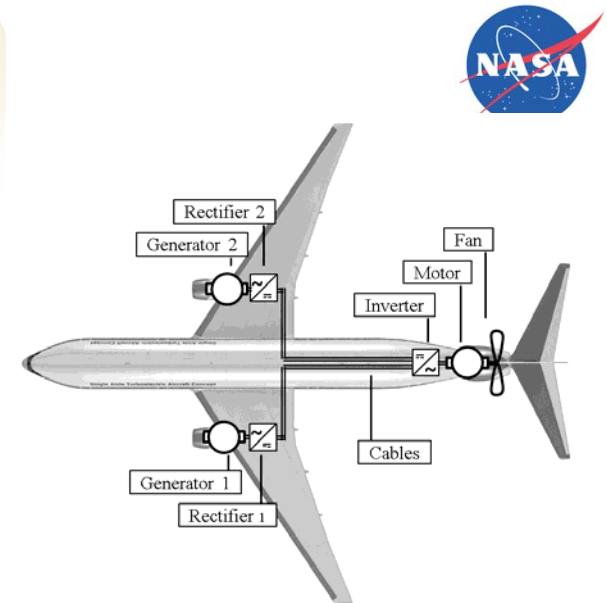
...Weight, Weight, Weight

Power system weights are very sensitive to

- Electrical Efficiency
- Component Specific Power
- Distribution Voltage

Key Material Technologies

- **Insulation Materials**—enable higher distribution voltage
- **Magnetic Materials**—increase switching frequency and reduce component losses
- **Advanced Conductors**—reduce weight. high risk / high payoff investment in new systems
- **Wide band gap semiconductors**—increasing frequency increases efficiency

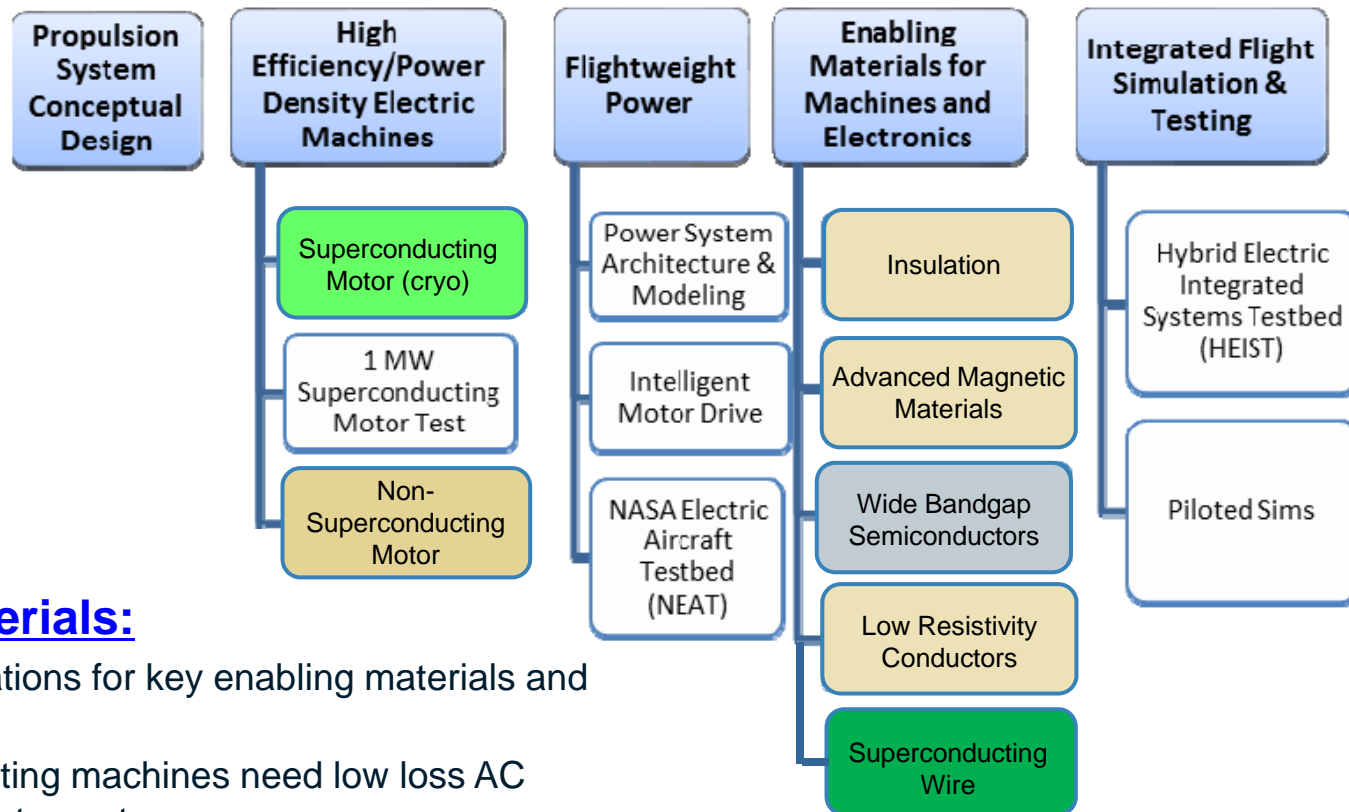


Ref: Jansen et al., AIAA, 2016

Hybrid Gas Electric Propulsion SubProject (HGEP)



Technical Areas:



Electrical Materials:

Component maturations for key enabling materials and subcomponents

- For superconducting machines need low loss AC portions – conductors, etc
- Must have higher voltages on the aircraft, thus insulation system development is required.
- Magnetic critical for efficiency, and likely enabling.
- Without higher conductivity material the electrical propulsion options for large vehicles is limited.



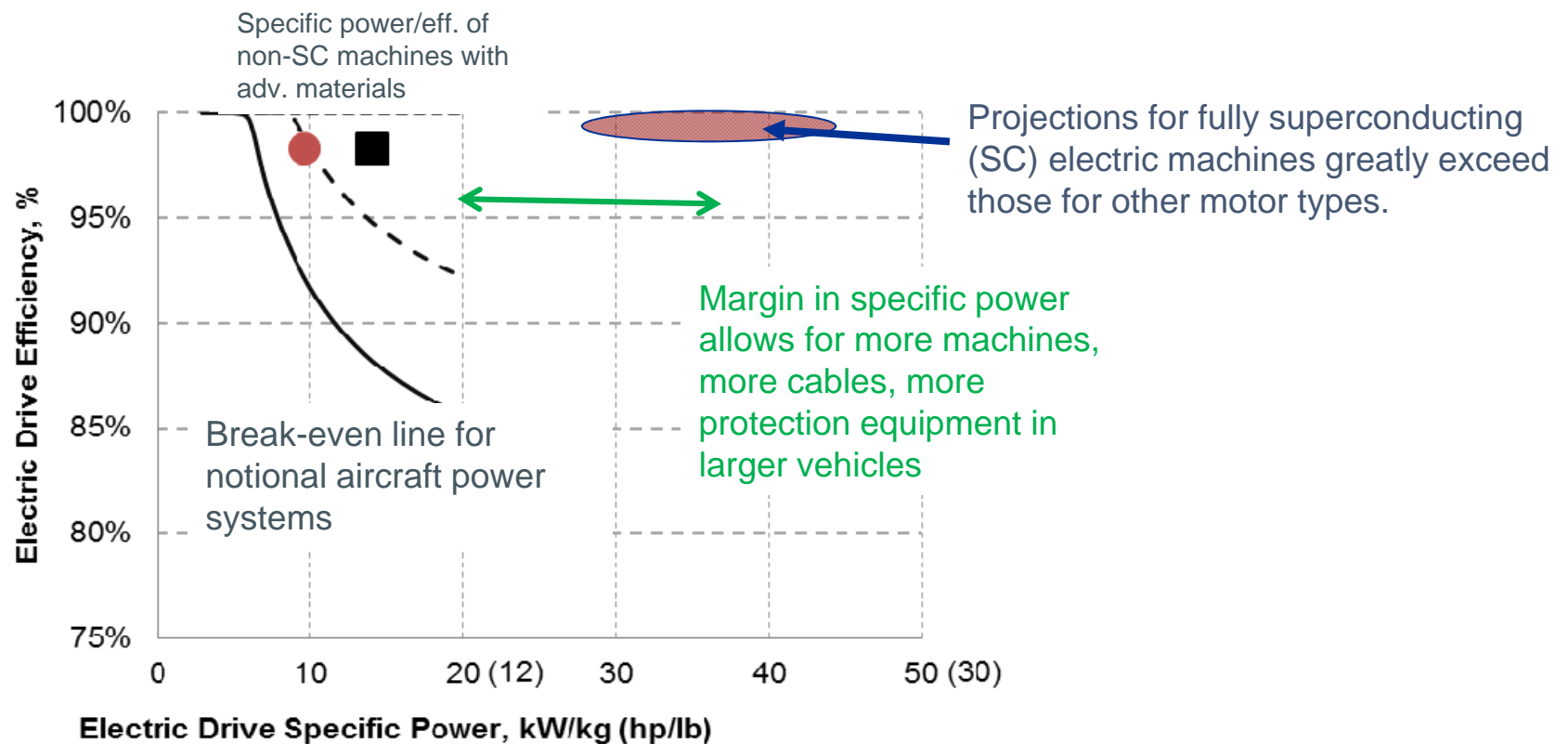
Electrical Materials

- Materials for Electrical Applications is a new research emphasis at NASA GRC.
- Not all technical areas are being addressed similarly.
 - Magnetic materials effort has reached critical mass in terms of equipment, staff, and external interactions.
 - Superconducting wire work is moving forward primarily via support to the one domestic vendor. Already used for DC, need to improve for AC. Some previous in-house work on nano MgB_2 particle production.
 - Insulation effort is gaining traction as the issues are better understood and external partners are engaged. Where will improvements make the most impact and which ones are most likely to have success.
 - High conductivity wire work is exploratory only, basically a 1-person effort.

Superconducting Motor



Superconducting (zero DC conduction loss) leads to much higher specific power and greatly enhances feasibility for distributed propulsion on larger aircraft



Conductors for Superconducting Motor



Although DC losses can be very low, AC losses are still a concern.

- Low-temp: 4 K Nb, NiTi metal wire NbTi (too much overhead)
- Med-temp: 20-30 K: MgB_2 wire via Hypertech (NASA emphasis).
Basically want a superconducting version of “Litz” wire
- High temp: 60 – 80 K: Rare-earth materials. Can produce flat tape but need wires to reduce eddy current losses at these temperatures. No work or support in this area. Aware of work by other groups in this area.

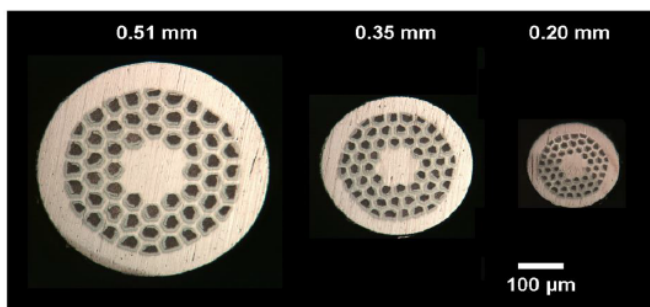
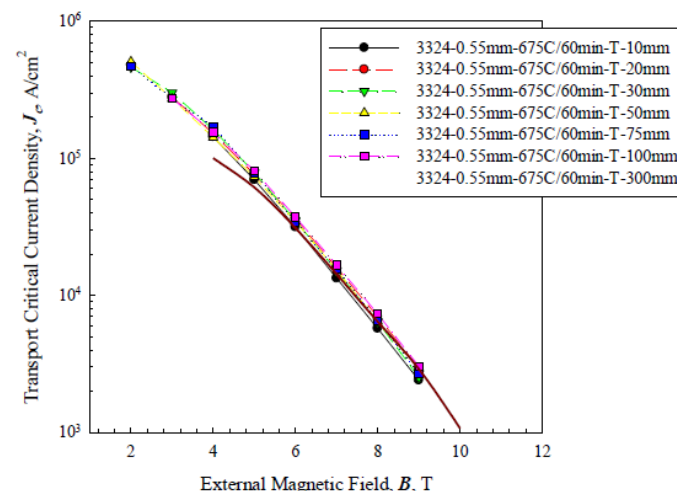
Low AC loss MgB_2 conductor development

Successful strand design recipe:

- small d_{eff}
- small twist pitch
- resistive matrix
- non-magnetic sheaths
- higher T_{op} (e.g. 20K); lower B_{op} (e.g. 0.6T)

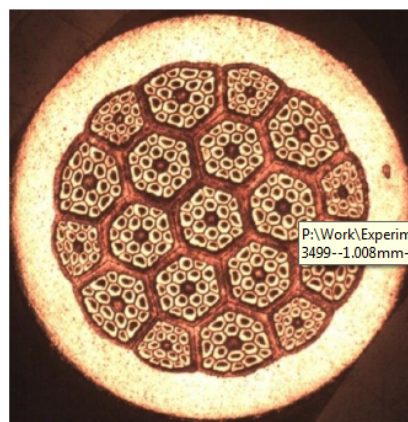
J_c measured with 10 μm filaments at 0.29 mm. Work progressing to get obtain 10 μm filaments with larger wire diameters.

J_c maintained with twist pitches as low as 10 mm.

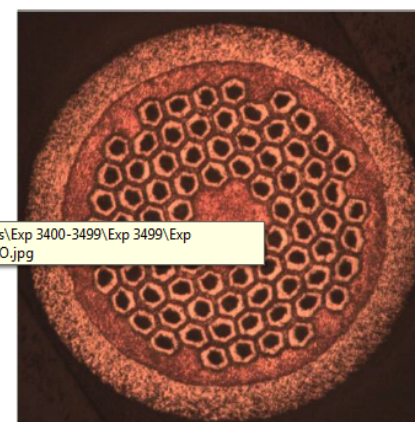


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Hyper Tech



342 filaments

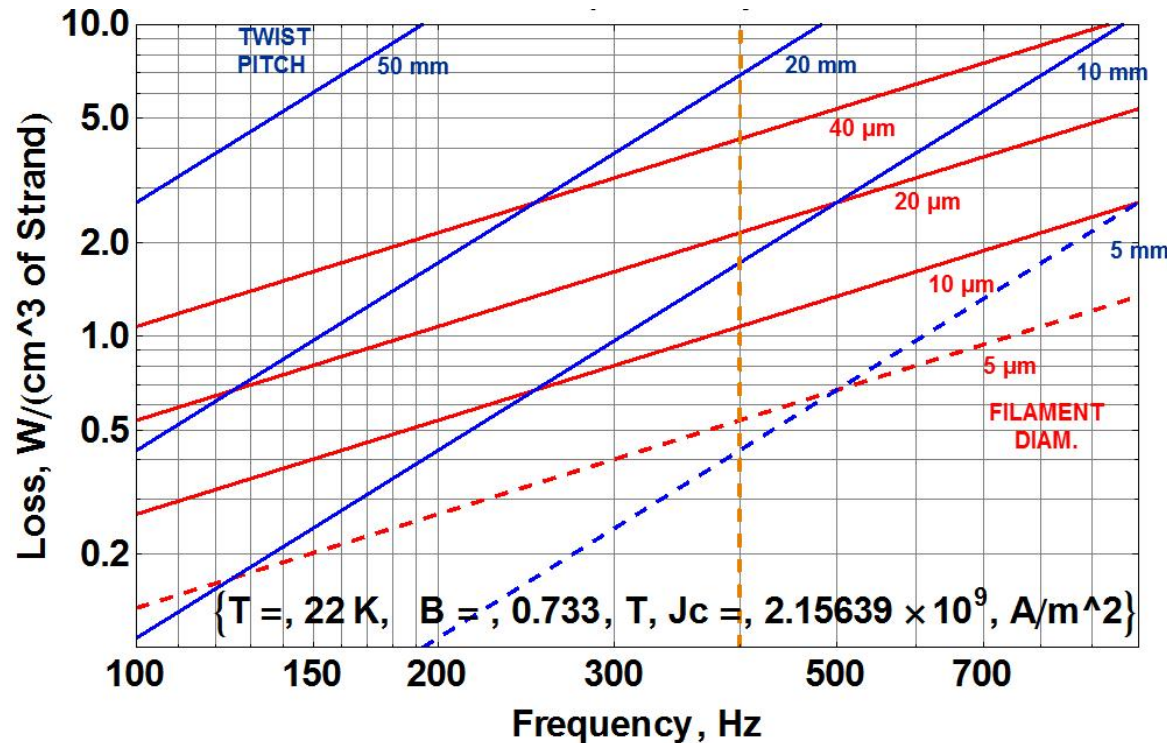


78 filaments

From Tomsic, et al, 2015 ASC Presentation, "Development of MgB_2 superconductor wire and coils for practical applications" Cryogenic Engineering Conference (Tucson, June 28-July 2, 2015)



Comparison of Hysteresis Loss (red curves) and Coupling Loss (blue curves)



Filament diameter of 10 μm and twist pitch of 10 mm have been achieved in MgB_2 fabrication trials. To further reduce losses, the 5 μm and 5 mm levels could be targeted.

Non-Superconducting Electric Machines



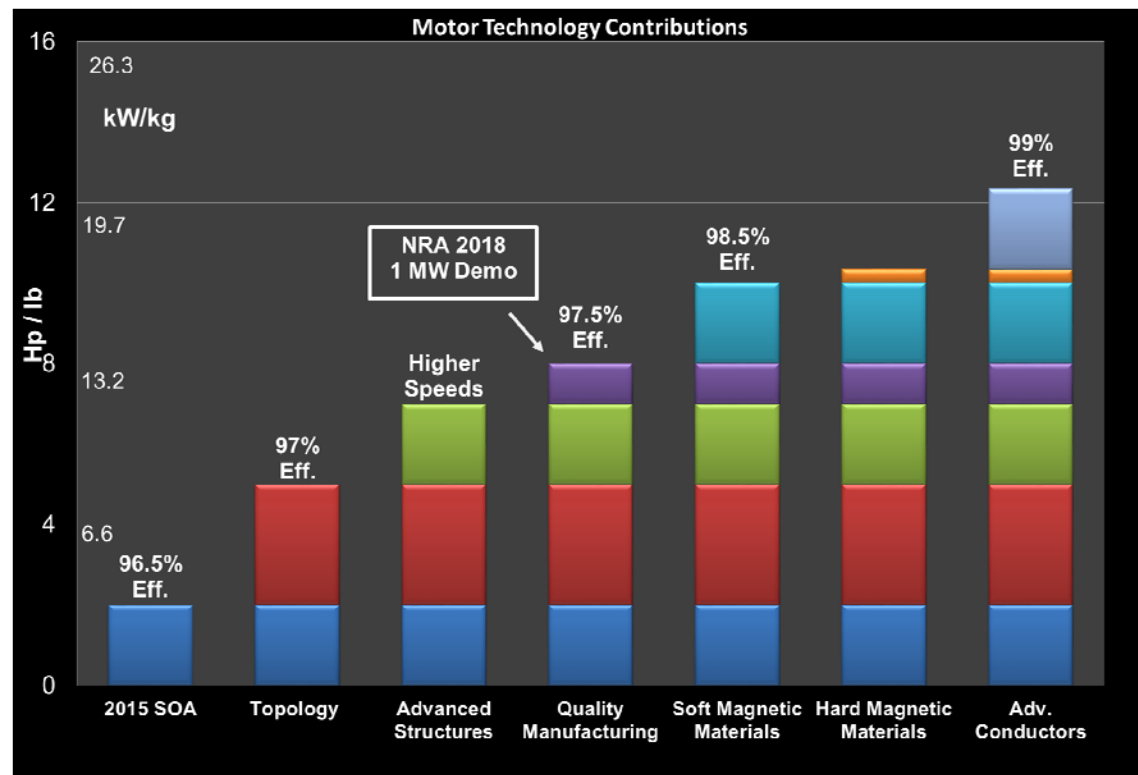
Rapid advancements in machines and power electronics makes flight weight electrical drives in the realm of feasibility

Improved motor/generator topology options enabled by advanced power electronics

Better specific power or power density due to aeronautic design & manufacturing processes.

Emerging wide-band gap semiconductors and advance soft magnetic materials enable high frequency operation with lower switching-frequency losses

New materials and fabrication developments will push specific power farther



Non-Cryo Machine - Enabling Materials Efforts



Need to **concurrently** tailor component materials for hybrid/turbo electric applications **and** design the power components that utilize these advance materials

Dielectrics and Insulation

Improve electrical insulation systems

- Study interface functionalization to enable new composite formulations
- Increase both the thermal conductivity and high voltage stability

Magnetic Materials

Enable high frequency operation with low electrical losses

- Collaborate with industry and academia to produce nano-crystalline magnetic material
- Perform alloy development and microstructural stability of soft magnetic alloys
- Support power electronic component development using new alloys

High Conductivity Copper

High risk, high pay-off investment in carbon nano-tube (CNT)/copper composites

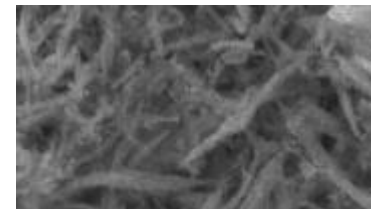
- Chemical engineered CNT interfaces
- Sorted CNTs to isolate the metallic conducting from semi-conducting
- SBIR investment in new manufacturing techniques



**Hi Voltage
Dielectric
Testing**



**0.75 miles of continuous
soft magnetic ribbon**



Cu-coated CNT's



Magnetic materials have not historically been an active research topic at NASA GRC

Motivation for Entering the Field:

- **Primary Driver** – Develop GRC expertise and capabilities in magnetic materials and initiate a presence in the application and research communities in response to the future direction of NASA GRC, which includes more material development for “green” power generation and conversion technologies.
- **Specific Goals** - Support the goals of the Advanced Air Transport Technology (AATT) Project by developing more capable soft and hard magnetic materials for use in motors and power conversion and control circuitry.

Role of Magnetics in Electric Machine Development



Motor analysis was used to study the performance sensitivity to new materials

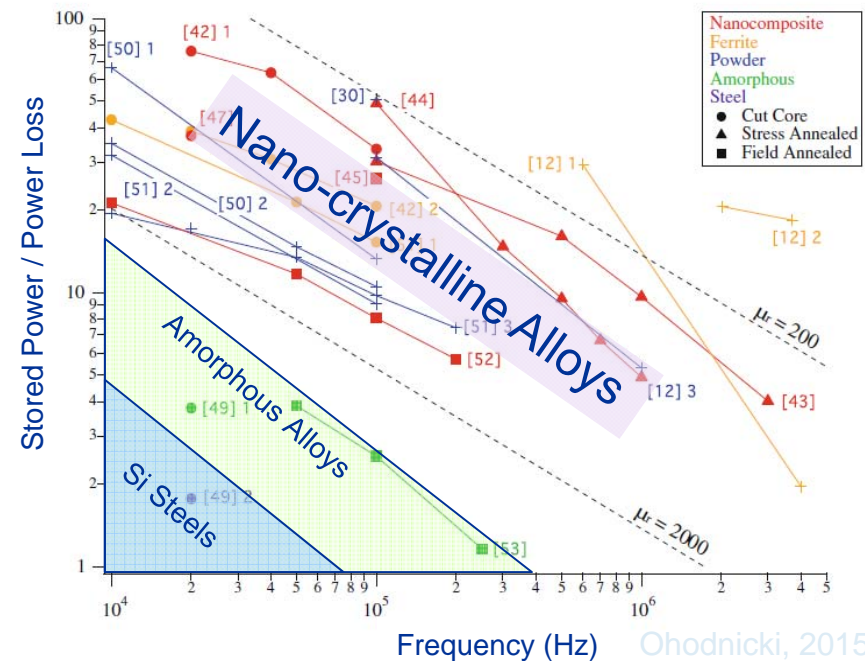
- ✓ High-frequency, low-loss magnetic materials have been shown to increase efficiency in electric machines and power electronics

Motors ~ 8000 rpm

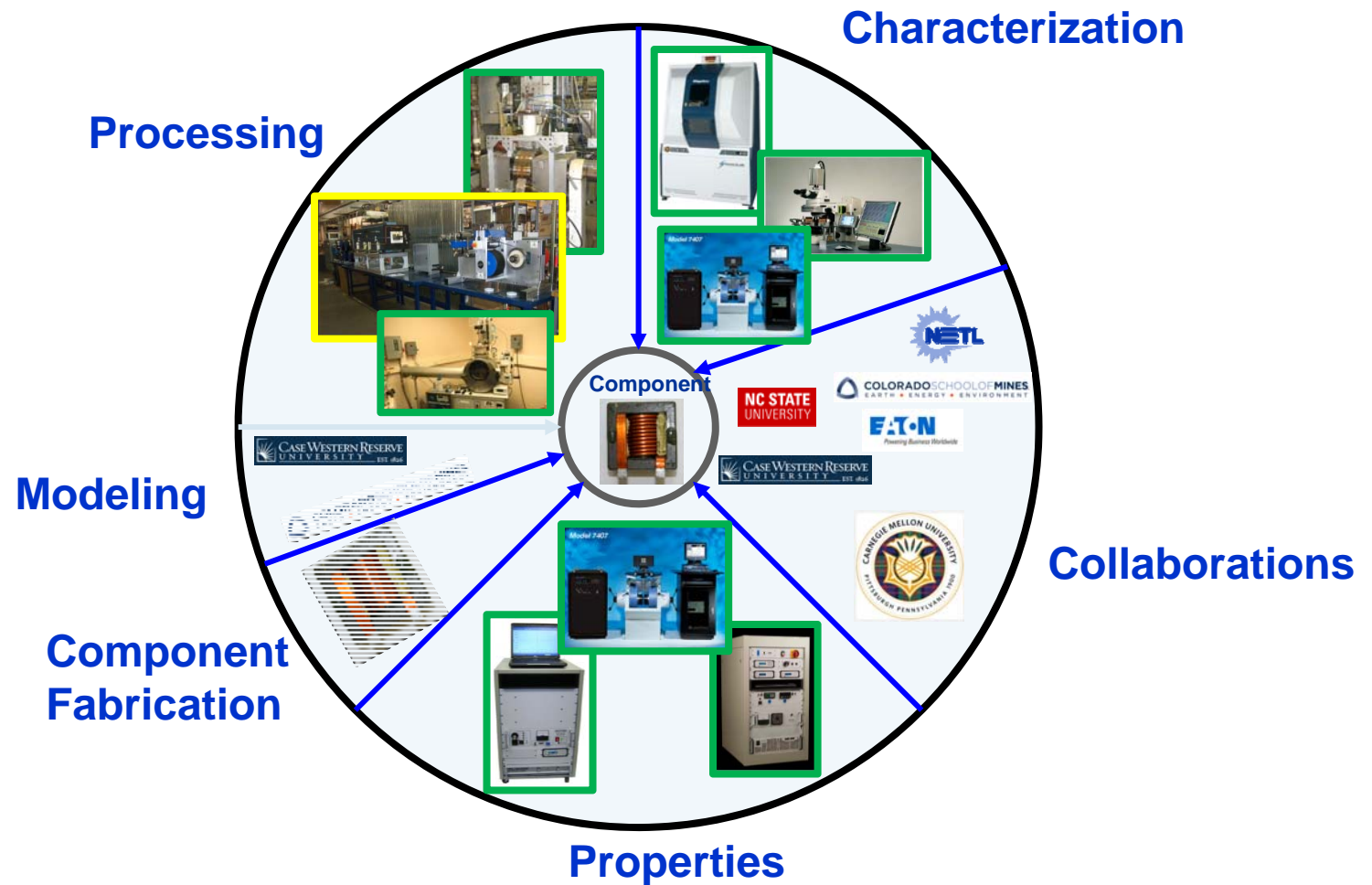
Power electronics ~20 kHz

- Machine (or electronic) efficiency goes up with switching frequency but magnetic losses also increase with switching frequency
- Amorphous and nano-crystalline soft magnetic materials have demonstrated lower losses at high frequencies

Power Ratio (stored inductive power/power loss) as a Function of Frequency



Magnetic Materials Program at GRC



It appears that magnetic material research will extend beyond just the AATT program, so we are establishing wide-ranging capabilities.

Goal is to establish capability for alloy development, characterization, and component fabrication for specific applications.

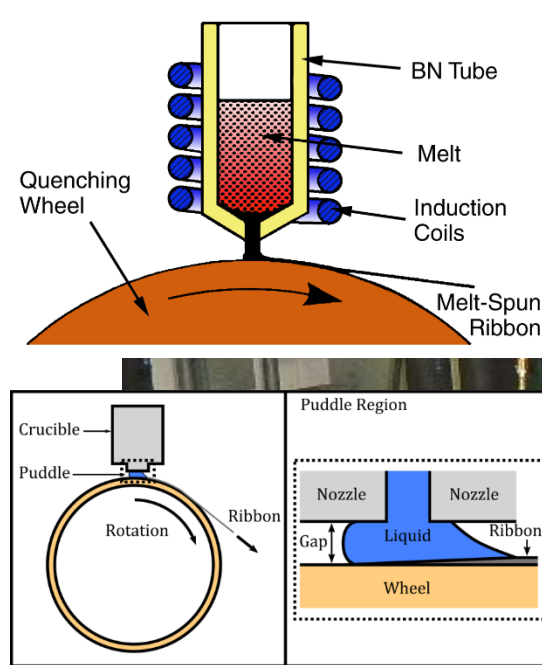


- Essentially completed lab build-up activities.
- Have made several new hires with experience in nanocomposite soft magnetics.
- Developing Co-based nanocomposite alloys for motor control inductor applications for NASA hybrid electric program.
- Collaborating with NETL on transformer alloy development and component fabrication for PV-to-Grid integration.
- Exploring potential for use in motor applications.
- Exploring potential for enabling miniaturization of circuit-board components.
- Always looking for outside collaborations.



Rapid Solidification (5-kg) Caster

Melted under argon cover gas. Casting is performed in air.



The ability to cast wide ribbons gives GRC unique capability in the field.

- Custom-Built unit (Spang/NASA)
- ~1 mile of ribbon with widths up to 50 mm

3-5 kg caster



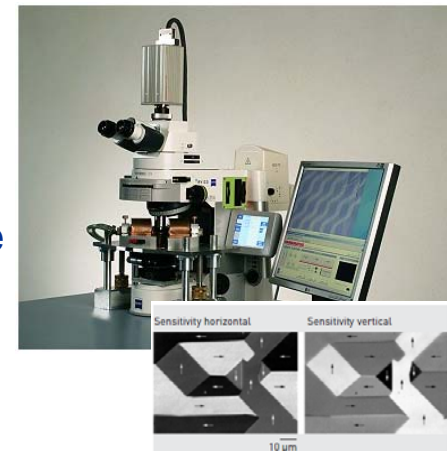
60 g caster



VSM



MOKE microscope for static and dynamic domain imaging



Sheet and toroidal B-H loop



Hysteresigraph for permanent magnet characterization



Custom loss-measurement system for use with non-sinusoidal excitation waveforms



High V and I toroidal pulse tester

High Conductivity Wire

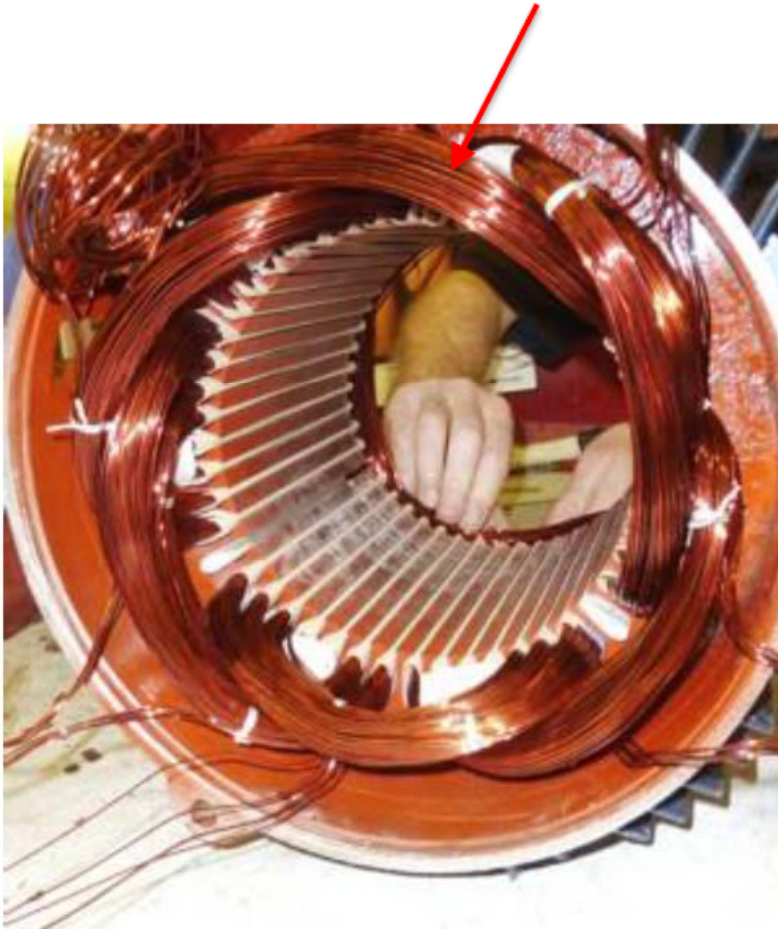


- Goal is to develop or identify non-superconducting wire with conductivity better than copper.... or at least lower the resistivity increase as a function of temperature.
- Weight reduction is the primary driver.
- Focus thus far has been evaluating vendor claims of improvements using small volume fraction additions of CNT
- Very small in-house effort. Probably not critical mass at this point.

Background and Motivation

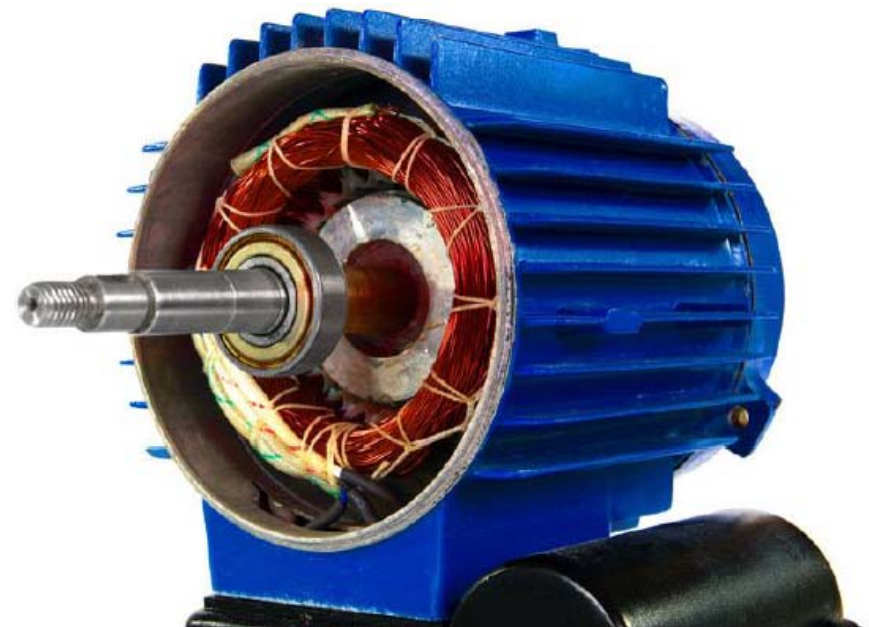


Improvements in Magnet Wire.



Program Goals

- Increase Motor Wire Conductivity
 - Lower i^2R losses;
 - Lower cooling requirements;
 - Higher power-to-weight ratio.
- Lower Wire Density



Experimental Procedures- Ampacity

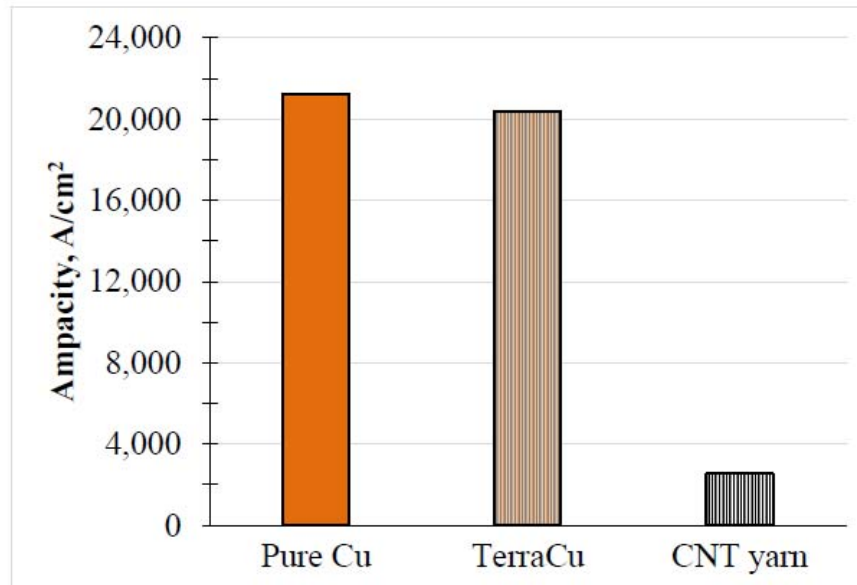
- Ampacity = max Amp/cm^2
 - 20 AWG pure Cu magnet wire;
 - 20 AWG Cu-5vol%CNT composite wire from NanoRidge Materials Incorporated;
 - 28 AWG MWCNT yarn from Nanocomp Technologies.



High Conductivity Wire



Improvement of ampacity has not been observed



Low longitudinal cooling is required to yield realistic results.

Average of 2 or 3 Ampacity measurements of Pure Cu, Cu-CNT composite TerraCopper, and a CNT yarn.

Currently evaluating sorted CNT and incorporating into wire to verify that conductivity is improved. Exploratory efforts are also underway at GRC to develop method for sorting CNTs.

Insulation Materials Development



Materials for Medium Voltage (1-10kV) Aircraft Distribution (altitude issues and volume constrained):

- Current aircraft system use limited distribution up to $\pm 270V$
- Breakdown voltage (minimum voltage that causes a portion of an insulator to become electrically conductive) is a function of gas pressure and gap length
- Exploring organic/inorganic composite system to meet aggressive new requirements

and High Thermal Conductivity:

- Thermal conductivity influences component efficiency and thermal management
- Looking for component specific improvements to increase electric machine specific power through improvements in
 - Potting Material
 - Slot Liners
 - Conductor Coatings



Batteries for Aviation

No AATT funding, some low-level “transformative concept funding”, one on LiO batteries and one on multifunctional structural systems.

What can be done now

- Current State of the Art Batteries have specific energy in the range of 150-250W-hr/kg
- 1-2 person airplanes using this battery technology have been demonstrated to TRL level 6
- Studies have shown that larger planes (9-50 PAX) can use electric technology for short range or in combination with range extenders (hybrid electric) when battery system have specific energies of 200-300 W-hr/kg

The benefit of advanced batteries

- Improvements in battery technology allows electric and hybrid electric systems to be extended into larger plane classes (50PAX and greater) and longer range missions (>200 miles)
- With these battery improvements the carbon impacts can be much more substantial than a system which relies primarily on jet fuel as it energy source
- Additionally, studies on smaller aircraft indicate that operational cost improvements can result from the greater use of battery systems for the short range.

Electrified Propulsion in Technology Suite



**Integrated Vehicles and
Concepts Evaluation**

**Efficient, Low
Noise Propulsors**

**Boundary-Layer
Ingestion Systems**

**Highly Efficient
Turbine Engines**

**Electrified Propulsion
Vehicle Configurations**

**Power Systems
Architectures**

**Advanced Electrical
Components**

